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SHAPE MEMORY EFFECT AND PERFORMANCE OF A NITINOL ENGINE

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ABSTRACT

This paper mainly focuses on the parameters that affect power output of Nitinol heat engine and phase transformation characteristics of Nitinol wire. In order to conduct this study, a two-pulley engine is fabricated and tested for power generation. Thermal parameters influencing the phase transformation of the Ni-Ti wire are determined. Results show that temperature of bath has a significant impact on power output. A mathematical model is developed for nitinol engines using the shape memory effect. Efficiency estimated using the model developed is compared with the Carnot efficiency. The comparative results of the efficiency were found to be inversely proportional to each other.

Keywords: Shape memory alloy, transformation temperature, phase transformation, austenite, martensite.

1. Introduction

Despite several deformations, shape memory alloys (SMA) can still remember their predetermined shape. SMA can be austenite, martensite or a mixture of them depending on the temperature. Normally nitinol transforms between the high temperature phase called B2 phase (also called as austenite - denoted by P) and the low temperature phase called B19 phase (also called as martensite, denoted by M). However due to thermal and mechanical effects such as thermal cycling, chemical composition, heat treatment, deformation may appear as an intermediate phase known as rhombohedral or R-phase (denoted by R) between the transformation of austenite to martensite which result in a two-stage transformation. Numerous elements can influence the transformation characteristics in NiTi-based shape memory alloy: variation in nickel content, after solution treatment aging, combined thermo-mechanical treatment, thermal cycling, doping with ternary alloying elements and processing techniques [1]. There are many factors which affect the power output of nitinol engine such as dimensions of the sink, diameter of nitinol wire, centre distance between two pulleys, number of turns of wire, bath temperature. Another factor of interest in the testing of the SMAs is heating/cooling rate which is impacted by heat transfer for a prolonged period, as observed in most of SMA's. Until now there are many publications which concentrate on the thermal and mechanical effects on the transformation behaviour of NiTi SMA [2]. However, the study of different parameters and transient study of SMA is still limited till date.

2. History of SMA

While conducting experiments with an alloy of gold (Au) and cadmium (Cd), an interesting phenomenon was discovered by Arne Oladder in 1932. When cooled, the Au-Cd alloy could be plastically deformed and then be heated to return to predetermined shape. This phenomenon is called the Shape Memory Effect (SME) and the alloys that show this behavior are called Shape Memory Alloys (SMA). At the Brussels World's fair, researchers Chang and Read demonstrated the Shape Memory Effect in 1958. By lifting a weight using an Au-Cd SMA, they showed that the SME could be used to perform mechanical work. After this, further research has been carried to determine other materials demonstrating the same phenomenon. In 1962, a group of U. S. Naval Ordnance Laboratory analysts, lead by William Beuhler, unearthed a huge revelation in the field of SME and SMA. An alloy of nickel and titanium was being tested for heat and corrosion resistance and they came to know that the alloy of nickel and titanium also exhibits SME phenomenon. The Ni-Ti SMA was found to have some advantages over already discovered alloys; they were significantly less expensive, easier to work with, and less dangerous (from health standpoint). These factors create interest and motivate others to research in the Shape Memory Effect and applications of shape memory effect [3].

2.1. Principle of Operation

Shape Memory alloys are the alloys of metallic materials which, when subjected to suitable thermal procedure, return to their original position. Au-Cd, Cu-Sn, Cu-Zn-(X), Cu- Al-Ni, In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu, and Fe-Mn-Si are some examples of these alloys. Between the two different phases, called austenite and martensite, a temperature and stress based shift occurs in the material's crystalline structure and thus the shape memory effect (SME) is observed. Soft phase is called martensite phase while hard phase is called austenite phase. Following is a simple example to explain SME in action.

Consider the SMA in austenite phase. If it is cooled below its phase transition temperature, the crystalline structure will change to hard phase, i.e. the martensite phase. If bar is plastically deformed by any means, say bending, and heated above transition temperature then the bar will return to its original position due to phase transformation from martensite to austenite. Let us make this phenomenon simpler by a simplified two-dimensional representation of the material's crystalline arrangement, as shown in Figure 1. Every single box represents a grain of material with border representing grain boundary. Due to grains, a heavily twinned structure is formed; this means that the grains are oriented across grain boundaries in a symmetric order. The twinned structure permits the interior cross section of individual grains to change while keeping the same interface with contiguous grains. Therefore, Shape Memory Alloys are fit for encountering large macroscopic deformations while maintaining considerable order within their microscopic structure. For instance, if a bit of SMA begins as austenite [Figure 1a], the interior nuclear grid of every grain is cubic, making grains with pretty much right points.

If phase transformation temperature is reached by cooling action, the crystalline structure changes to martensite [Figure 1b] and the grains breakdown to the structures like jewels. Note that the grains are oriented in different directions for different layers. Presently, if adequate anxiety is connected, the martensitic structure shown in Figure 1b will begin to yield and "de-twin" as the grains re-situate, such that they are all balanced in the same direction [Figure 1c]. This conduct can be better comprehended by looking at a regular anxiety strain bend for the martensite stage [Figure 2].

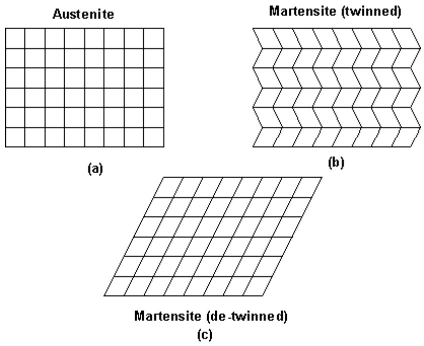


Figure 1. Material Crystalline Arrangement during the Shape Memory Effect

At first, for little hassles, the structure shown in Figure 1b acts flexibly from area 0 to 1. At position 1, the material yields and de-twinning happens somewhere around 1 and 2. At 2, the martensitic structure is totally de-twinned as shown in Figure 1c. In the blink of an eye, a second flexible area happens from 2 to 3. At 3, an enduring plastic distortion starts that is not recoverable by the SME.

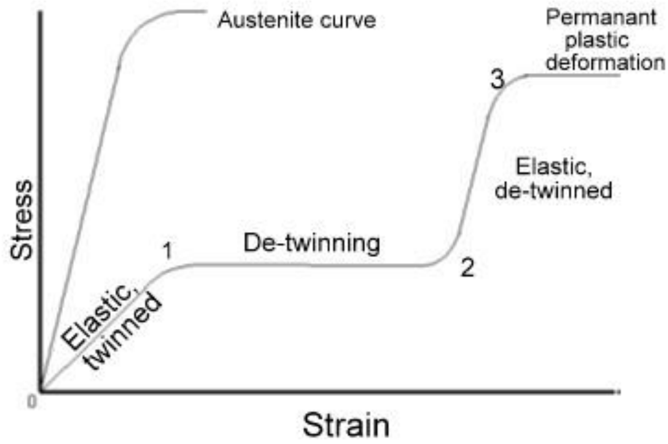


Figure 2. Stress -Strain Relationship of a Shape Memory Alloy

2.2. Nickel-titanium (Ni-Ti) shape memory alloy

Out of all the Shape Memory Alloys that have been developed so far, Nickel-Titanium (Ni-Ti) has proven to be the most beneficial and flexible in engineering applications. Some of the following characteristics of Ni-Ti make it better than the other SMA's: better ductility, recoverable motion is fast, excellent corrosion resistance (comparable to series 300 stainless steels), high biocompatibility, stable transformation temperature, and the ability to be electrically heated for shape recovery.

Ni-Ti SMA is the paired, equiatomic intermetallic compound of nickel and titanium. It is made up of approximately 50 atomic% Ni and 50 atomic% Ti. The valuable qualities of the intermetallic compound are moderate solvency range for overabundance Ni or Ti as well as for most other metallic elements, and ductility comparable to most ordinary alloys. The solvency permits Ni-Ti to be alloyed with different components which enables improvements in mechanical properties and stage change temperature (where stage change temperature is taken to mean AF). Adding additional Ni to the binary compound (up to 1% extra) strongly depresses the phase transformation temperature and increases the yield strength of the austenite. Iron and chromium can likewise be added to bring

down the transition temperature. By shifting these and different components, the change temperature can be fluctuated from –200 to 110°C (- 325 to 230°F). Copper can be used as an additive to decrease the hysteresis and lower the deformation stress (de-twinning stress) of the martensite. Table 1 shows the key physical properties of equiatomic Ni-Ti SMA.

Table 1 Properties and phase transfromation of Nitinol

Properties	Austenite	Martensite
Melting temperature,̊ C	1300	
Density, g/cm^3	6..54	
Resistivity, Ω-cm	Approx. 100	Approx. 70
Thermal conductivity, W cm/^{o} C	18	8.5
Corrosion resistance	Similar to 300 series stainless steel or titanium alloys	
Young's Modulus, GPa	Approx. 83	Approx. 28
Yield strength, Mpa	195 to 690	70 to 140
Ultimate tensile strength, MPa	895	
Transformation temperature,̊ C	-200 to 110	
Latent heat of transformation,̊ C	167	
Shape memory strain	8.5% maximum	

2.3. Manufacturing and shaping of Nitinol

Manufacturing Nitinol SMA and shaping it for a specific purpose is very tough task. Inert atmosphere has to be maintained while melting Ti as it is a very reactive element. Plasma-arc melting, electron-beam melting, and vacuum induction melting are some of the common methods used during this process. Standard hot-forming and cold-working processes are used in order to initially shape the Ni-Ti ingots. During cold working, alloy must annealed frequently as it gets work harden very quickly. By minimizing the stress needed to de-twin the martensite and increasing the strength in the austenite phase, we can improve SMA's performance. For this, we can use processes like work hardening and heat treatment processes. Machining Ni-Ti through cutting methods is difficult, as is welding, soldering, and brazing. For creating specific shapes grinding, shearing, and punching are better methods. The "memory configuration" that is giving shape memory to SMA is done by holding the part in desired shape, and then heat-treating at 500 to 800°C (950 to 1450°F). Prefabricated SMA elements like wire, rod, ribbon, strip, sheet, and tubing are provided by companies like Dynalloy, Inc. and Shape Memory Applications, Inc. This companies also provides custom element to user specification.

3. Methodology

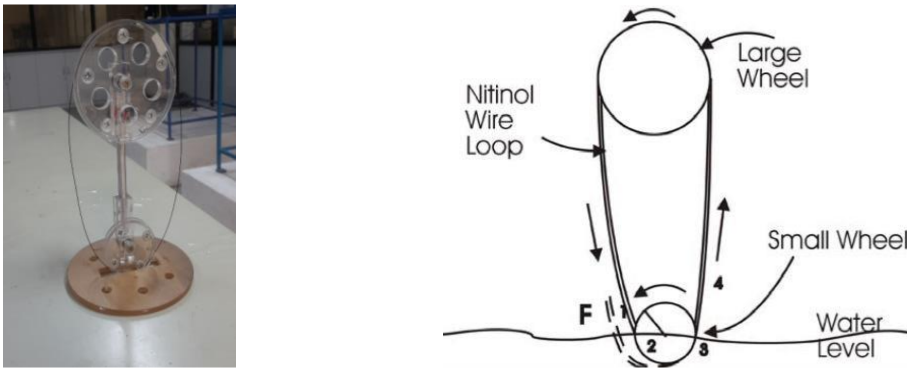
3.1 Modeling

Model consists of simply two pulleys. A nitinol wire of 0.5 mm diameter is run between two pulleys.

Two pulleys were made up of glass. Diameter of the bigger pulley is 70mm and diameter of the smaller pulley is 40mm. Center distance between the two pulleys can be varied by fixing adjustable bolt at different positions. Solidworks model of two pulley system helps to visualize the model and the challenges in fabrication.

3.2 Experimental setup

The engine [Figure 3a], generates power by using nitinol wire loop. The loop made of nitinol runs in between the two pulleys. Hot water on hot side and cool ambient air on cool side is used by this device in order to perform action. The smaller wheel of engine is partially dipped in a hot liquid. Memory given to the nitinol loop wire in engine is 'straight' shape. Whenever a part of loop gets in contact with a hot liquid, it gets heated above its transition temperature and tries to straighten out. Figure 3a explains the phenomenon. From Figure 3b, it is clear that at position 1, nitinol wire is straight and cool. As the wire travels from position 1 to position 2, it gets bent around the small glass pulley and comes in contact with hot liquid. As the wire moves from position 2 to position 3, it comes in contact with hot water and thus gets heated above its transition temperature due to which it tries to straighten out. As the wire tries to straighten out, it takes form the form shown by dotted line. While doing so, the wire exerts a tugging force of magnitude F along the loop. As the wire moves from position 3 to 4, it comes in contact with ambient air due to which its temperature decreases and, thus, austenite phase starts converting to martensite phase. As the wire moves from position 1 to position 4, it travels over the bigger pulley and a sufficient long time is available for the wire to cool below its transition temperature; the wire get ready for another cycle. In simple words, one side of loop stiffens due to high temperature while the other side i.e. air side of loop, cools and relaxes. A wheel pulley rotates due to mechanical force. Sometimes it becomes necessary to jump start the engine by giving rotation to the bigger pulley manually. Interestingly, the engine hasn’t a set rotational direction. Whichever way it is started it will continue to rotate. The engine can also be powered by using solar energy. A magnifying lens focusing sunlight on the smaller glass wheel also supplies sufficient temperature gradient to power the engine.



(a) (b)

Figure 3. Working principle of nitinol engine

3.3 Experiments performed

Aim of this experiment is to find out variation of speed of nitinol engine with respect to decrease in temperature of bath. Water is takeen as a heating fluid as it is easily available and it has many advantages over other fluids as heating source. Water is heated to 90 degrees Celsius with help of conventional heating process and then the heating source is removed. Water is then poured in a flask and nitinol engine is placed over the flask. The temperature on cool side is room temperate which was found to be 32 degrees Celsius during the experiment.

As explained in working principle in the above section, the engine starts rotating. Speed of engine is measured with the help of laser tachometer. Figure 4 shows the laser tachometer used for measuring speed of nitinol engine in RPM. As the time passes, temperature of water bath goes on decreasing due to heat loss to surrounding. Variation in speed of the engine is measured with the help of laser tachometer.

Figure 4. Laser tachometer

4. Results and Discussion

4.1. Transient analysis: -

Table 2 shows the variation of speed of engine with respect to decrease in temperate of water bath. Figure 5 shows the output of these results in graphical form. From Table 2 and the aforementioned graph we can conclude that,

- Engine does not start unless temperature of bath reaches 45 degrees Celsius
- From 45 to 75-degree Celsius speed goes on increasing with the bath temperature
- After 75-degree Celsius, speed remains constant irrespective of increase in temperature of bath

Table 2 (a) and (b) Variation of speed with temperature of bath

(a)

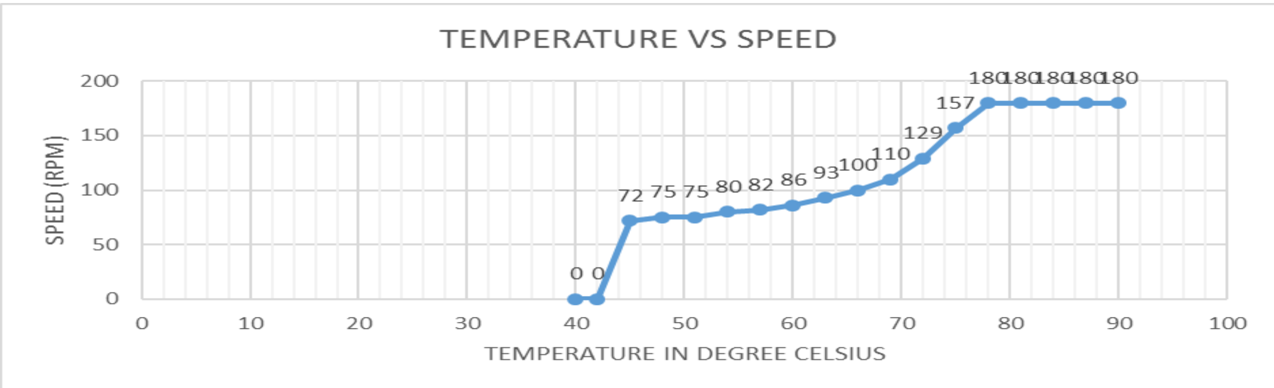
S. No	Temperature (degree Celsius)	RPM
1	90	180
2	87	180
3	84	180
4	81	180
5	78	180
6	75	157
7	72	129

8	69	110
9	66	100

(b)

S. No	Temperature (degree Celsius)	RPM
10	63	93
11	60	86
12	57	82
13	54	80
14	51	75
15	48	75
16	45	72
17	42	0
18	40	0

Figure 5. Graph of temperature Vs speed



5. Mathematical model for finding efficiency

NITINOL engine is fed by the heat energy of LP water by means of heat transfer at the boundary of Wire – LP water. Let us consider this process similar to heat transfer of metal surface at the boundary with the moving water. Then, the intensity of the flow of heat transfer will be equal to: [21]

$$W = (\sigma_0 + \sigma_1\sqrt{v}\,)\, S_W\, \Delta T \quad \text{Watt} \tag{1}$$

Where, V is the velocity of heated section of NITINOL engine with the length of l_w relative to water, $\Delta T = T_{warm} - T_{cool}$ is the temperature gradient (thermal head) – the difference between the temperatures of LP water, T_{warm} (hot) and T_{cool} (cold) water, and σ_0 ,σ_1 are the coefficients of heat transfer equal to [21]

$$\sigma_0 = 350\ W/m^2k\ ,\ \sigma_1 = 2100\ (W/m^2k).(s/m)^{1/2} \tag{2}$$

The contact surface Sw of wire with LP water for engine is determined by,

$$S_W = n2\pi r_0 w = 1*2\pi*0.5*10^{-3}*0.37 = 1.16238*10^{-3}\ mm^2 \tag{3}$$

Where r_0 = radius of nitinol wire which is 0.5 mm in our case

And l_w = length of nitinol wire running between two pulleys =370 mm in our case

Apparently, W is the sum of two summands:

$$W= W_Q+W_A \tag{4}$$

Where, WQ is a part of W consumed continuously for heating of wire at inverse martensitic transition M→A, and WA is a part of W at the expense of which engine develops the power.

Q is the quantity of heat transferred to wire for specific time at operating conditions, necessary for M→A transition

$$Q=M.C_P.\Delta T \quad \text{Watt} \tag{5}$$

The value C_P is the average value of the product of specific heat capacity of nitinol C, from the experiment, it is known that in the case of nitinol [21]

Where ,

$$C_P=5.2*106\ J/m^3k \tag{6}$$

And M= mass flow rate of wire through fluid (m^3/s)

$$M=\pi r^2{}_0\, V \tag{7}$$

By definition, the thermal efficiency is the relation between the work and the quantity of heat received by engine at heating, i.e.

$$\eta=W_A/Q \tag{8}$$

Here W_A is considered instead of W because only W_A is a part of work developed by engine while other part i.e. W_Q is absorbed by engine

Hence,

$$W_A= W/2 \tag{9}$$

Now, let us find thermal efficiency of engine according to Carnot, for comparing Carnot efficiency of engine with actual efficiency consider the readings obtained while performing experiment of temperature vs. speed.

At 90 degrees' Celsius temperature of water, speed given by NITINOL engine was N=180 RPM

According to Carnot, efficiency is determined as

$$\eta_K =1- (T_{cool} / T_{Warm}) \tag{10}$$

In this case, T_{COOL} = Temperature of cool air (i.e. room temperature) = 305 K T_{WARM}= Temperature of hot water = 363 K.

Putting this values in Eq(10), we get

(11)

$$\eta_k = 0.1597 = 15.97\%$$

Now for finding actual efficiency of engine we will make use of Eq (8),

Putting values of Eq(2) and Eq(3) in Eq(1) and substituting ΔT=363-305=58 k, we get

$$W=(350+2100^*)*1.16238*10\text{-}3*58 \qquad (12)$$

$$0\text{Now } V=(\Pi DN/60) \qquad (13)$$

Where D= diameter of rotating wheel = 70 mm

$$V = \frac{\pi * 0.07 * 180}{60}$$

$$V = 0.6597 \text{ m/sec} \qquad (14)$$

Putting Eq (14) in Eq (12), we get,

$$W = 138.58 \text{ W} \qquad (15)$$

From Eq (9)

$$W_A = \frac{138.58}{2} = 69.29 \text{ W} \qquad (16)$$

Now from Eq (5),(6) AND (7),

$$Q=M.C_P.\Delta T$$

$$Q=\pi*(0.5*10^{-3})^2*0.6597*5.2*10^6*58$$

$$Q=156.2753 \text{ W} \qquad (17)$$

Putting Eq (16) and Eq (17) in Eq (8), we get

$$\eta = \frac{69.29}{156.27} = 0.4433 = 44.33\% \qquad (18)$$

We can compare the Carnot and actual efficiency of nitinol engine now by using Eq (11) and Eq (18); actual efficiency of nitinol engine is greater than Carnot efficiency. This happens because nitinol engine does not require any work output for its operation like Carnot cycle requires. Thus, it is not limited to Carnot efficiency. However, Carnot efficiency of each case is obtained just for comparison with other engine working on Carnot cycle.

For different cases, comparison between actual and Carnot efficiency is tabulated in Table 3.

The tabulated results are represented by graph in Figure 5.

Table 3. Efficiency calculation

Sr. no	T_{cool} (K)	T_{warm} (K)	ΔT (K)	V_{rel} (m/s)	W (w)	W_A (w)	Q (w)	η_k	η
1	305	363	58	0.6597	138.59	69.29	156.27	0.1597	0.4434
2	305	360	55	0.6597	131.42	65.71	148.19	0.1527	0.4434
3	305	357	52	0.6597	124.25	62.12	140.10	0.1456	0.4434
4	305	354	49	0.6597	117.08	58.54	132.02	0.1384	0.4434
5	305	351	46	0.6597	109.91	54.95	123.94	0.1310	0.4434
6	305	348	43	0.5754	97.11	48.55	101.05	0.1235	0.4805
7	305	354	49	0.4728	102.18	51.09	94.61	0.1384	0.5399
8	305	342	37	0.4030	72.39	36.19	60.91	0.1081	0.5942
9	305	339	34	0.3665	64.08	32.04	50.90	0.1002	0.6294
10	305	336	31	0.3408	56.79	28.39	43.15	0.0922	0.6570
11	305	333	28	0.3151	49.76	24.88	36.03	0.0840	0.6904
12	305	330	25	0.3000	43.63	21.81	30.69	0.0757	0.7107
13	305	327	22	0.2924	37.99	18.99	26.27	0.0672	0.7228
14	305	324	19	0.2748	32.04	16.02	21.33	0.0586	0.7511
15	305	321	16	0.2748	26.98	13.49	17.96	0.0498	0.7511
16	305	318	13	0.2638	21.59	10.79	14.01	0.0408	0.7704

From Table 3, we conclude that efficiency of engine goes on increasing as the temperature gradient decreases. This happens because the decrease in W is very less as compared to the decrease in Q. Due to this ratio, efficiency increases.

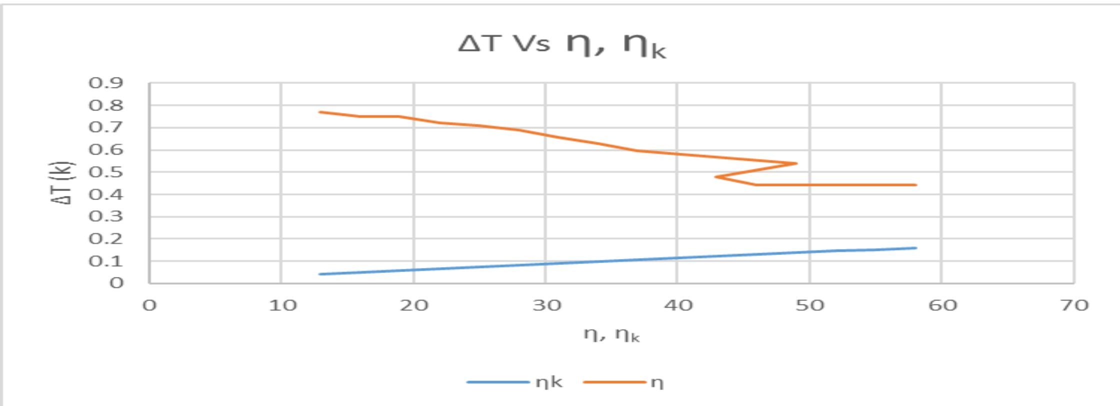


Figure 5. Graph of temperature difference Vs efficiency

6. Summary

Thermal parameters influencing the speed of the Ni-Ti engine are determined. Results show that the temperature of bath plays a major role on power output. From mathematical results we can conclude that the actual efficiency of nitinol engine is inversely proportional to the temperature gradient.

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